NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3852

FLIGHT MEASUREMENTS OF THE VIBRATIONS ENCOUNTERED BY A TANDEM HELICOPTER AND A METHOD FOR MEASURING THE COUPLED RESPONSE IN FLIGHT

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SUMMARY

A discussion of flight-test and analysis methods for some selected helicopter vibration studies is presented. The use of a mechanical shaker in flight to determine the structural response is reported.

The analysis methods described are based on the determination of the power spectral density of the force and of the response due to the force through use of analog frequency-analysis techniques. Results obtained by these methods are presented to show the coupled response of a helicopter in flight for two different blade configurations. The flight results are compared with results of ground tests to show the presence of coupling in flight. Available theoretical calculations of the coupled structural frequencies are included to show how these approximations compare with flight data. Some of the limitations of these tests and suggestions for refinement of flight vibration testing are discussed.

In addition, natural-vibration measurements of some of the more important harmonics of rotor speed are presented for a range of speed and power conditions.

INTRODUCTION

As helicopters have become larger and more flexible, the magnitude of the vibrations associated with these machines has increased. Available information indicates that high vibration levels are attributable to many sources, the primary sources being aerodynamic loading of the rotor blades and resonance amplification of the structure.

Because of speed changes and periodic variation in the angle of attack encountered by the rotor blades, alternating air forces act on the blades once per revolution and at multiples of this frequency. In general, only those forces which have a frequency that is a multiple of the number of blades per rotor are transmitted to the structure in the vertical direction. The alternating forces which are transmitted are usually small in comparison to the weight, but if the frequency of the transmitted force is near the structural resonance frequency, then large amplification may occur. In some of the early designs, attempts were made to lower the vibration level by setting the natural frequencies of the helicopter components, such as the blades, fuselage, and engine, between the multiples of rotor speed. This approach to the problem was only partially successful. Some calculations indicated that coupling of rotor blade bending and fuselage bending might bring about structural resonance at frequencies where none was apparent from considerations of each component separately. It became apparent that the helicopter must be treated as a coupled system and that the effect of the interaction of the components (blades, fuselage, engine, etc.) is important. The problem is to design and calculate more accurately so that determination of the coupled response frequencies of the structure is possible before the prototype is built.

As a result of the increasing importance of this problem, a flight investigation of the vibrations encountered by a typical tandem helicopter has been undertaken at the Langley Aeronautical Laboratory. Concurrently a theoretical investigation (ref. 1) was undertaken to determine the coupled natural frequencies of a helicopter whose physical characteristics are practically identical to those of the helicopter used for the flight tests. The purpose of the present investigation was to determine the importance of coupling and to find out which structural components are of primary importance in calculating resonances. The helicopter chosen for this investigation was known to have a high vibration level under certain conditions; any changes that were made to this vibration level by the test methods would be recognized.

The response of the helicopter structure to mechanical shaking was measured at the front rotor under actual flight conditions. In addition, some flight surveys were made for a range of speed and power conditions and the natural vibrations were recorded.

EQUIPMENT AND INSTRUMENTATION

Helicopter

A typical tandem helicopter with three-blade rotors was used for the investigation. During the tests the helicopter was equipped with two sets of blades (metal and wood) having different mass and frequency characteristics. (See fig. 1 for details.)

Instrumentation

Motions of the structure were measured by using MB vibration pickups (type 124). Three components of velocity (vertical, longitudinal, and transverse) were measured at the front rotor, the rear rotor, and directly under the pilot's seat (fig. 2). There were two pickups on the engine, and one on the fuselage near the engine which measured the vertical velocity only. Time histories of the output of these velocity pickups were recorded by an oscillograph. The velocity-pickup—oscillograph combinations have response curves which are similar to that of figure 3. Response corrections have been applied to all the data. To provide the in-flight excitation a mechanical shaker (force varies as frequency squared) was mounted on the front-rotor gear box to shake in a vertical direction only. A tachometer measured the frequency of the shaker.

The flight conditions (airspeed, pressure altitude, etc.) were obtained through use of standard NACA recording instruments synchronized with the oscillograph by means of a common timing circuit.

Analysis Equipment

The frequency-analysis equipment consisted of a two-channel, variable-filter-width heterodyne harmonic analyzer and associated playback and recording equipment. This device provides a reading of the mean square of the signal passed by a tunable filter with a specified accuracy of ±1/2 decibel. The absolute accuracy with which the center frequency of the filter is known is estimated to be within 2 cps. In this case the data were analyzed at 20 times normal tape speed and therefore the center frequency is known to within 0.1 cps. The effective band width of the filter used for the data analysis was about 0.30 cps.

TESTS AND ANALYSIS METHODS

Ground Tests

Ground vibration tests were conducted with the same instrumentation as for the flight tests. The rotors (from the flapping pins out) were removed and the fuselage was suspended at the rotor hubs (fig. 4) by soft springs (shock cord). The frequency of the fuselage as a whole on this spring suspension was less than 1 cps and would therefore have little effect on the elastic modes of the structure. The vibration response of the structure to excitation by a mechanical shaker was measured at the locations shown in figure 1. The shaker, which was mounted on the front-rotor gear box, applied a sinusoidal force $F = 0.45(\text{Frequency})^2$ in a vertical direction over the frequency range of 8 cps to 24 cps.

Since the natural frequency and effective mass of the rotors vary with rotor speed, only in flight are all the dynamic and aerodynamic characteristics of the helicopter correctly represented. In order to obtain some numbers for calculation purposes, the rotors were replaced by known weights and the change in fuselage response with change in weight was measured. The results of the measurements are shown in figure 5. It can be seen that the first bending frequency of the fuselage, as indicated by the peaks, is decreased from 13.6 to 9.8 cps as the weight at each rotor is increased from 0 to 250 pounds.

Flight Tests

In a helicopter the natural vibrations are present to varying degrees for all flight conditions. Since the largest shaker available had a force output of about 75 pounds at the 3/revolution frequency it was necessary to conduct the tests at flight conditions of minimum vibration. If the tests had been conducted at other flight conditions, the shaker force might have easily been overshadowed by the natural input, and the analysis would then be very difficult if not impossible. In order to show the effect of changes in rotor speed, a series of rotor speeds was selected which encompassed the allowable range (250, 273, and 290 rpm). In the test helicopter the 3/revolution natural input occurs near a structural resonance frequency and structural vibrations are amplified. The vibrations in this frequency region are of most interest for several reasons - structural fatigue, pilot and passenger comfort, and so forth. The frequency of the shaker was therefore set to change slowly from 8 cps to 17.5 cps, the frequency range of interest. The sweep rate of the shaker was set at 6 seconds per cycle, which allowed approximately 1 minute for the traverse. The flight plan for the tests consisted of setting the power, airspeed, and rotor speed at predetermined values and holding them constant while the frequency of the shaker was varied from 8 cps to 17.5 cps. A similar run was made while the frequency of the shaker was varied in the reverse direction; thus two runs were made for each flight condition. Data were obtained for each of the three rotor speeds previously mentioned (250, 273, and 290 rpm). At 250 rpm the natural vibrations were so large that the additional response due to the mechanical shaker could not be separated in the analysis. The results presented in this paper are therefore for two rotor speeds only, 273 and 290 rpm.

The flight tests for the natural-vibration survey were conducted in a little different manner. The helicopter was trimmed for level flight at 45 knots and a desired power setting. The pilot then slowly traversed the range of speed above and below this trim speed, allowing as much as 3 minutes for the complete traverse. The rotor speed was set for 273 rpm and remained at this setting throughout the tests. Data were taken for four power conditions: take-off (37 in. Hg manifold press.), cruise

(30 in. Hg manifold press.), low (20 in. Hg manifold press.), and autorotation (15 in. Hg manifold press.), over a speed range of approximately 15 to 90 knots.

Analysis Methods

In this helicopter the fuselage is considered to be similar to a free-free beam and the response of the structure is assumed to be the vertical motion of the front rotor resulting from the vertical force input of a mechanical shaker. Thus,

$$\text{Response} = \frac{\text{Output}}{\text{Shaker input}}$$

This relationship holds over the complete frequency range traversed by the shaker except for a small region near the 3/revolution frequency. The reason for this limitation is that the phase angle between the shaker force and the natural input force can have any value (0° to 360°) as the shaker sweeps through this 3/revolution frequency region, and these forces can either add or subtract.

Analog frequency-analysis techniques (ref. 2) were used for the data analysis. The sample records shown in figure 6 were taken for flight conditions where the vibration was a minimum, a forward speed of 55 knots and a rotor speed of 290 rpm. The frequency of the shaker is indicated by a revolution counter, the trace of which is shown in the lower part of the figure. Since the response measured at the front rotor in a vertical direction is considered representative of the structure, and because of the time required to work up the data, only this trace was analyzed.

The record was divided into four 15-second lengths for analysis to provide a larger ratio of signal to noise. The vertical velocity at the front rotor and the shaker force for each of the four sections of the records were transcribed manually from the original oscillograph record onto magnetic tape. The tape records were formed into loops and run through an electronic frequency analyzer. The output of the analyzer is in the form of a variation with frequency of the average square velocity or force passed by the filter as it sweeps through the frequency range. This output divided by the filter area provides an estimate of the power spectral density of the velocity and force time histories averaged over the length of the record, expressed as $\overline{(\text{in./sec})^2}/\text{cps}$ and $\overline{\text{lb}^2}/\text{cps}$, respectively.

To illustrate the method for determining the coupled response of a helicopter in flight, figure 7 is presented. The power spectral densities of the vertical velocity and shaker force at the front rotor are plotted against frequency for the four 15-second lengths of record, indicated by the numerals 1, 2, 3, and 4. During the first 15-second part of the record the helicopter responds to the shaker, as indicated by the velocity at the front rotor, in the frequency band swept by the shaker (8.5 to 11.6 cps). Since the natural vibrations are always present, a measurement of the first, third, and sixth harmonic inputs is also obtained. During the second 15 seconds of the record, the shaker sweeps from 11.6 to 13.9 cps and the output spectrum shows the helicopter responding in this frequency band and also provides a second measurement of the natural vibrations. It will be noted that, during the third 15-second portion of the record, the output due to the shaker and that due to the natural input are vectorially additive and no estimate of response to the 3/revolution frequency is obtained. In the fourth part of the record the helicopter responds in the frequency band swept by the shaker (15.9 to 17.6 cps) and an additional measurement of the natural vibrations is supplied. By breaking the record into four parts, it was possible to obtain three measurements of the 3/revolution component and four measurements of the 1/revolution and 6/revolution components without taking a separate record with the shaker not operating.

An indication of the variation of the natural input during the 1-minute record can be seen in the change in levels of the 1/revolution and 6/revolution components. There appears to be about ±15 percent variation in the components over the total length of the record. With the information from figure 7, the coupled response of the helicopter can now be determined. The total velocity-output spectrum (fig. 7(a)) is divided by the shaker force spectrum (fig. 7(b)) point by point, except in a small region near the 3/revolution frequency for reasons already explained in this section. The resulting curve is shown in figure 8(b) and is a faired line through all the data points. In the small frequency band near the 3/revolution frequency, indicated by the hatched region in figure 8(b), the response curve is unreliable. Data for the remaining response curves were handled in a similar manner.

RESULTS AND DISCUSSION

In order to show the effect of blade configuration and rotor speed, coupled-response curves for two types of blades (wood and metal) are presented for two rotor speeds. The flight-determined coupled-response frequencies are compared with those determined by the theory of reference 1 for the wood blade configuration. Curves are also presented which show how the natural vibrations vary with forward speed for some selected flight conditions.

Coupled Response With Wood Blades

In figure 8 a comparison is shown of the coupled-response curves for 273 and 290 rpm. The two curves are similar, both having two peaks, but the relative heights of the peaks are different for the two rotor speeds. There appears to be an effect due to change in rotor speed; that is, when the rotor speed decreases, the height of the second peak decreases. It was concluded from the trend in the second peak for the two curves and from other data that there would be only one peak in the coupled-response curve for 250 rpm. It appears that at 250 rpm the natural input frequency and the fuselage coupled frequency would be so close together that large structural amplification would occur. This conclusion seems quite compatible with the fact that the records could not be unscrambled for this rotor speed.

Coupled Response With Metal Blades

In figure 9 a comparison is shown of the coupled-response curves for 273 and 290 rpm. Here again the two curves are similar, both having two peaks, with the relative heights of the two peaks being different for the two rotor speeds. The effect of rotor speed is indicated by a reduction in height of the second peak as rotor speed decreases. The data through which these curves were faired had more scatter than those for the wood blades. Because the blade input is higher for the metal blades, the ratio of blade input to shaker force input is larger and it is harder to separate the responses in the frequency analysis. Near the 3/revolution frequency the separation of the response due to the shaker from that due to the natural input is very unreliable, as indicated in figure 9.

The fact that the minimum level for the wood blades is lower than the minimum level for the metal blades near 13.5 cps evidences a possible change in the coupling of the helicopter components (blades, fuselage, etc.).

Comparison Between Flight and Ground Tests

In figure 10 is shown a comparison of one of the flight response curves (273 rpm, wood blades) with the ground response curve for 100 pounds (45 percent flapping weight) at each rotor. The ground response curve for 100 pounds at each rotor was selected because the effective mass of each rotor was calculated to be 100 pounds in the first bending mode. Both the flight and ground measurements of vertical motion were taken at the front rotor. The comparison shows the presence of coupling. The ground response curve has one peak, whereas the flight response curves have two peaks in the frequency region of interest (10 to 16 cps).

Comparison of Flight Results With Theory

Since flight results are sometimes the only means for checking theoretical calculations, figure 11 is presented to show a comparison between flight measurements and calculations by the theory of reference 1. The calculations, which were made by using blade parameters that correspond to those of the wood blades of this paper, predict three modes of motion in the frequency range from about 12 to 15 cps. From an examination of several raw flight records, it was concluded that the two flight-measured structural modes are predominantly symmetrical. It was not possible to tell from the vibration records whether the predicted antisymmetric mode was present. However, since this antisymmetric mode is not one involving fuselage resonance, the fuselage acts primarily as a mass and very large blade motions are needed to produce any effect on the fuselage. On this basis it is not surprising that the antisymmetric mode would not be excited enough in flight to be measurable. The agreement between flight results and theory leaves room for improvement, but it does show how approximations for design purposes can be made. The calculations are helpful, but since damping is not included the relative importance of the various modes cannot be determined. In a study of vibration suppression, a knowledge of the relative importance of the modes would be essential.

Suggestions for Refined Flight-Test Technique

During the workup of the data some difficulties were encountered which were the result of flight-test techniques. Some suggestions for refinement in flight-testing techniques and some of the difficulties encountered are discussed in the following paragraphs.

Mechanical shakers were found to be very sensitive to speed control when exciting multidegree-of-freedom systems such as a helicopter. For the shaker used in the present investigation, the size and type of the drive motor was such that speed control was marginal. While cycling over a frequency range, the shaker tended to "lock in" whenever a resonance frequency was reached. This response of the shaker force to structural motion causes peaks in the average force input and motion output, frequency bands are skipped, and information is lost. In addition, the frequency is not known more precisely than to ± 0.1 cps and when the velocity spectrum is divided by the force spectrum, scatter is introduced in the coupled-response curves.

It was found from an examination of several runs for the same flight condition that the phase angle between the shaker force and the rotor force was different for each run. For this reason it was decided that a different flight-testing technique would be necessary for any future tests. The following flight-test technique is suggested for vibration response measurements. The forced excitation could be provided by a hydraulically actuated mass the frequency of which would be electronically controlled. With this type of shaker the amplitude of the force would be variable and, in addition, could be held constant over the frequency range. The same technique of sweeping would be used over most of the frequency range, except that within ±5 percent of any harmonic of rotor speed (1/revolution, 3/revolution, 6/revolution, etc.) a point-by-point approach would be used. In addition, the shaker would not be set on any frequency corresponding to a harmonic of rotor speed, since the phase between shaker input and structural output would be unknown, and the response at this frequency could not be determined. The response curve would be faired through these small regions near the harmonics of rotor frequency.

In the analysis the processing of the data could be greatly speeded up by recording the output of the vibration pickups directly on the tape, bypassing the transcriber. The data measurements could be handled more easily by using a flight tape recorder or by telemetering the information to the ground where it would be recorded on tape. This procedure would also allow the determination of the phase between the pickup locations.

Natural-Vibration Measurements

The flight technique used for these measurements enabled the pilot to cover a range of speed for a minimum of flight time. Through the use of the previously mentioned frequency-analysis methods, it was possible to obtain time histories of some of the more important harmonics of rotor speed, such as the 3/revolution and 6/revolution components. For these time-history records, the filter was set at the component frequency (13.5 cps for 3/revolution and 27.0 cps for 6/revolution) and the entire length of tape was run through the analyzer. Figure 12 will serve to illustrate a time history of one of the components, in this instance the 3/revolution. This is a 5-second sample record and is shown at 13.5 cps, the 3/revolution frequency. It can be seen that the 3/revolution component was not steady but varied somewhat in amplitude, even during this short record. This amplitude variation is apparently independent of airspeed.

In order to show the variation with airspeed of the harmonics of rotor speed, the 3/revolution and 6/revolution time-history records were read for 5-knot increments of airspeed, no attempt being made to average the variations in these components. The data points so obtained were converted to units of average displacement and are plotted against airspeed in figure 13.

In figure 13 the variation of the principal harmonics of rotor speed with airspeed are shown for four power conditions (take-off, 37 in. Hg;

cruise, 30 in. Hg; low, 20 in. Hg; and autorotation, 15 in. Hg). All the natural-vibration data presented here were measured at the front rotor in a vertical direction and are for the metal blade configuration. In addition, all of the results shown in figure 13 were obtained out of the ground-effect region. The scatter of the data points is indicated by the width of the bands in figure 13. The 3/revolution component in this figure apparently is different for each power condition; however, two facts are evident: (a) in the low-speed range the higher the power setting, the higher the amplitude of vibration, and (b) the speed for minimum vibration is different for each power condition. In figure 13(b) the left portion of the 3/revolution curve was recorded on one day and the right portion on another, and the result illustrates how the records can vary from day to day.

For take-off and cruise power conditions the 6/revolution component shows its highest level of vibration near the low end of the speed range. The 6/revolution component for take-off power rapidly decreases to about 0.007 inch near 25 knots, and remains about constant over the remainder of the speed range. For cruise power the 6/revolution component slowly decreases to about 0.005 inch near 50 knots and remains near this amplitude over the remainder of the speed range. The 6/revolution component for the low and autorotation power conditions remains nearly constant over the speed range at about 0.006-inch amplitude.

It can be pointed out here that the relative magnitudes of the harmonic components change for different flight conditions. This variation could account for the fact that prototype changes which reduced vibration for one flight condition might be ineffective or adverse for another.

Measurements near transition in ground effect.- It was not possible to make a frequency analysis of the vibration measurements during transition because of trace overlap; therefore it was decided to analyze the records near transition to compare the output of all the vibration pickups. Transition is generally used to refer to a flight condition intermediate between hovering and the speed for minimum power, and is defined in this paper as the speed region from 15 to 30 knots. Since flow asymmetries and associated vibrations tend to reach a peak in this region, the term is loosely used to refer to the speed where vibration first reaches a maximum. In table I are given all the measured vibratory amplitudes (near transition) in terms of average displacement for each of the two blade (metal and wood) configurations. It can be seen in the tables that the major vibrations are at the rear rotor, the longitudinal component being the largest. The raw flight records show that 4 seconds later, when the helicopter is experiencing transition conditions, the vertical component at the front rotor is the largest. From rough measurements of the raw records it is estimated that the vertical component at the front rotor (metal blades) has increased fivefold to about 0.05-inch double amplitude, whereas the components at the rear rotor have decreased markedly. In addition, it was concluded from an examination of the raw records (metal blades) for each of the two flight conditions previously mentioned that the fuselage mode of motion was primarily symmetrical. There is some evidence of the presence of an antisymmetric fuselage mode which could account for the change in the ratio of the vertical components of the front and rear rotors as the helicopter enters transition.

Estimate of force input at front rotor.- In order to define the magnitude of the force input at the front rotor and to illustrate how response curves of the type shown in figure 8 can be used, the following example is presented: For calculation purposes continue the response curve of figure 9(a) (273 rpm) through the hatched area; the response at the 3/revolution frequency in the hatched area of this figure is considered to be accurate within ±30 percent. By making use of the survey data of figure 13, an estimate of the natural force input (metal blades) at the front rotor can be made for each of these power conditions over the speed range. For example, the response at the front rotor near the 3/revolution frequency is about 3.6×10^{-3} in./sec/lb (fig. 9, 273 rpm) and the average displacement of the 3/revolution component for take-off power is 0.02-inch double amplitude near 25 knots (fig. 13). Converting 0.02 inch at 3/revolution (13.7 cps) to velocity gives 0.86 in./sec; dividing this value by 3.6×10^{-3} in./sec/lb indicates about 240 pounds of vertical force input to the front rotor. This value of force is estimated to be correct within ±75 pounds. If survey records of the natural vibrations were available for the wood blade configuration, similar estimates of the force could also be made.

CONCLUDING REMARKS

A method is presented which enables the coupled structural response of a helicopter in flight to be determined. This method, which includes the use of a mechanical shaker for flight excitation, provides a great saving in flight and analysis time by using the technique of sweeping rather than a series of steady conditions. Results are presented which show the coupled response of a helicopter in flight for two different blade configurations. A modified flight-testing technique is suggested for future work. In addition, natural-vibration measurements of some of the more important harmonics of rotor speed are presented for a range of speed and power conditions.

The presence of the coupling of the components (fuselage, blades, etc.) is evidenced by the fact that the flight response curves show two peaks whereas the ground response curves show only one. The coupled-response curves for the two blade configurations (metal and wood) show the effect of change in rotor speed; that is, when the rotor speed is decreased the height of the second peak decreases.

A comparison of calculated coupled frequencies from available theory with those determined from flight tests indicates that the theory can give fair approximations to the coupled frequencies.

Numerical results on natural vibrations have been obtained and serve to confirm the expectation that significant variations in the relative harmonic contents of these natural vibrations occur with variations in flight conditions. The ability to make these measurements of the natural-vibration spectra should help in the evaluation of prototype helicopters and should point the way to changes for overall improvement.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., August 7, 1956.

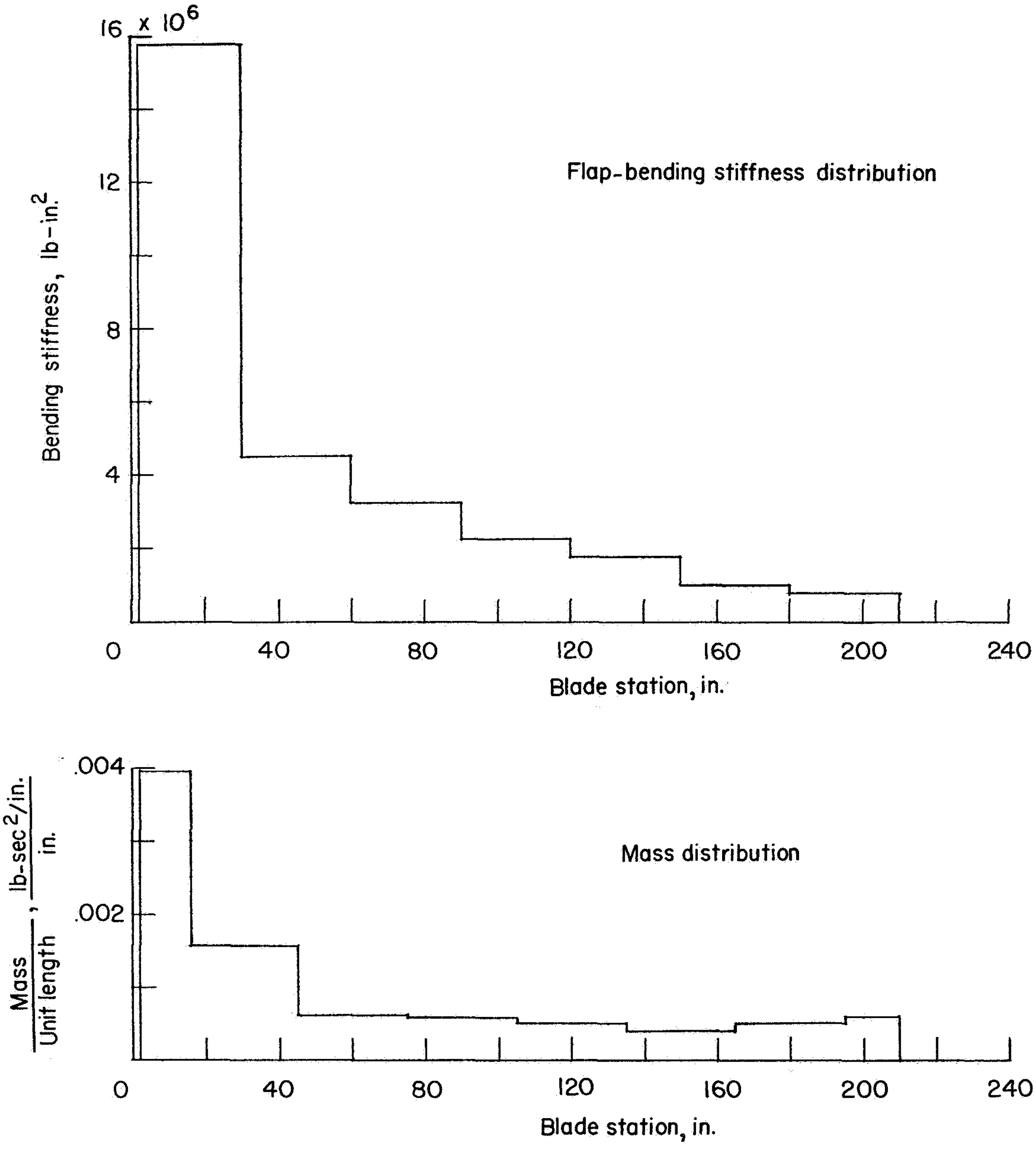
REFERENCES

1. Brooks, George W., and Houbolt, John C.: Analytical Determination of the Natural Coupled Frequencies and Mode Shapes and the Response to Oscillating Forcing Functions of Tandem Helicopters. NACA TN 3849, 1956.

2. Smith, Francis B.: Analog Equipment for Processing Randomly Fluctuating Data. Aero. Eng. Rev., vol. 14, no. 5, May 1955, pp. 113-119.

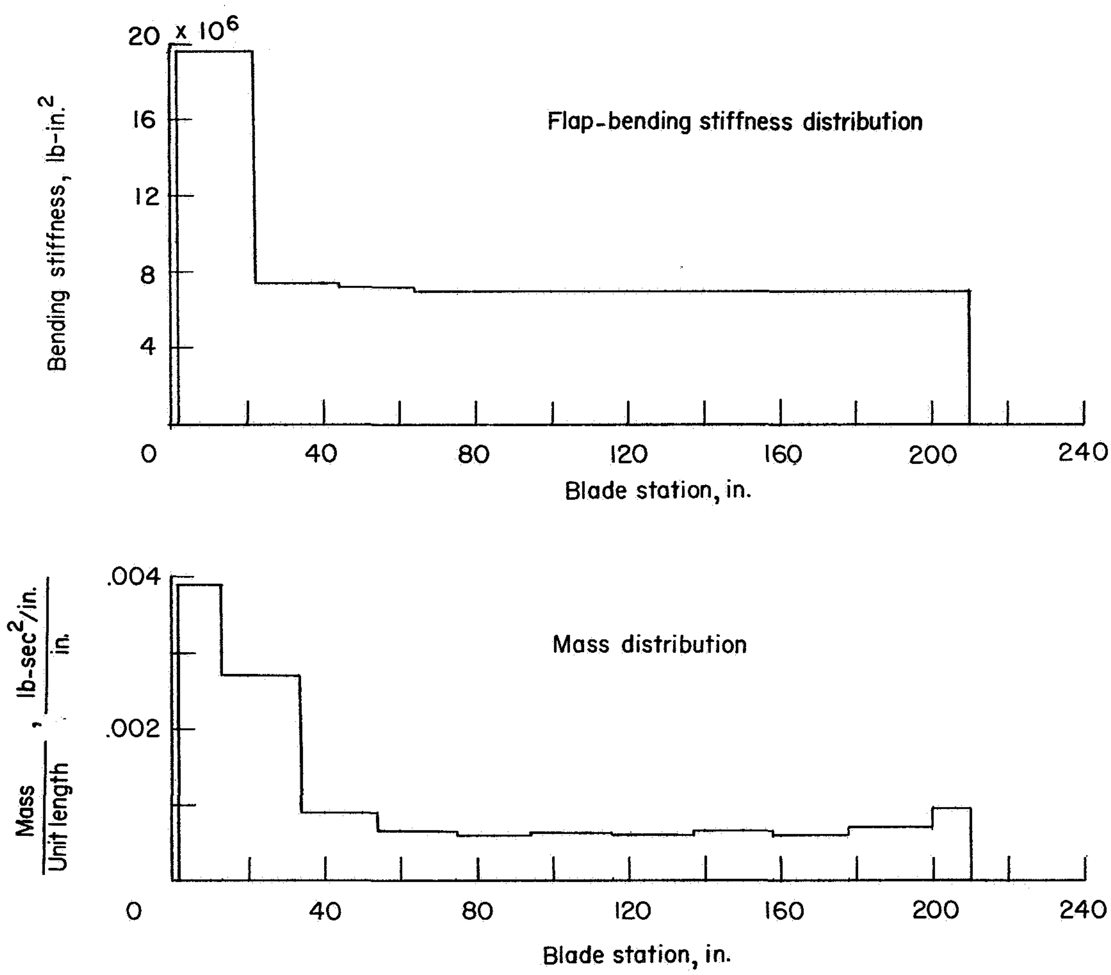
TABLE I.- VIBRATION MEASUREMENTS MADE DURING APPROACH TO TRANSITION

Vibration-pickup location	Double amplitude of vibration, in., for -		
	1/revolution	3/revolution	6/revolution
Wood blades			
Pilot, longitudinal	0.0043	0.0016	0.0010
Pilot, vertical	.0090	.0103	.0027
Pilot, transverse	.0132	.0039	.0013
Front rotor, longitudinal	.0160	.0033	.0020
Front rotor, vertical	.0015	.0075	.0010
Front rotor, transverse	.0070	.0045	.0010
Rear rotor, vertical	0	.0061	.0020
Rear rotor, longitudinal	0	.0114	.0040
Engine, rear, vertical	0	.0141	0
Metal blades			
Pilot, longitudinal	0.0078	0.0054	0
Pilot, vertical	.0071	.0077	.0016
Pilot, transverse	.0170	.0088	0
Front rotor, longitudinal	.0120	.0117	0
Front rotor, vertical	.0074	.0094	.0020
Front-rotor, transverse	.0074	.0053	0
Rear rotor, vertical	0	.0153	0
Rear rotor, longitudinal	.0230	.0362	0
Rear rotor, transverse	.0210	.0306	0
Engine, rear, vertical	0	.0125	0
Engine, forward, vertical	.0096	.0078	0
Fuselage, vertical	.0120	.0051	0



(a) Wood blades (natural frequency, 4.0 cps).

Figure 1.- Mass and stiffness characteristics of the two sets of blades used for the tests.



(b) Metal blades (natural frequency, 5.5 cps).

Figure 1.- Concluded.

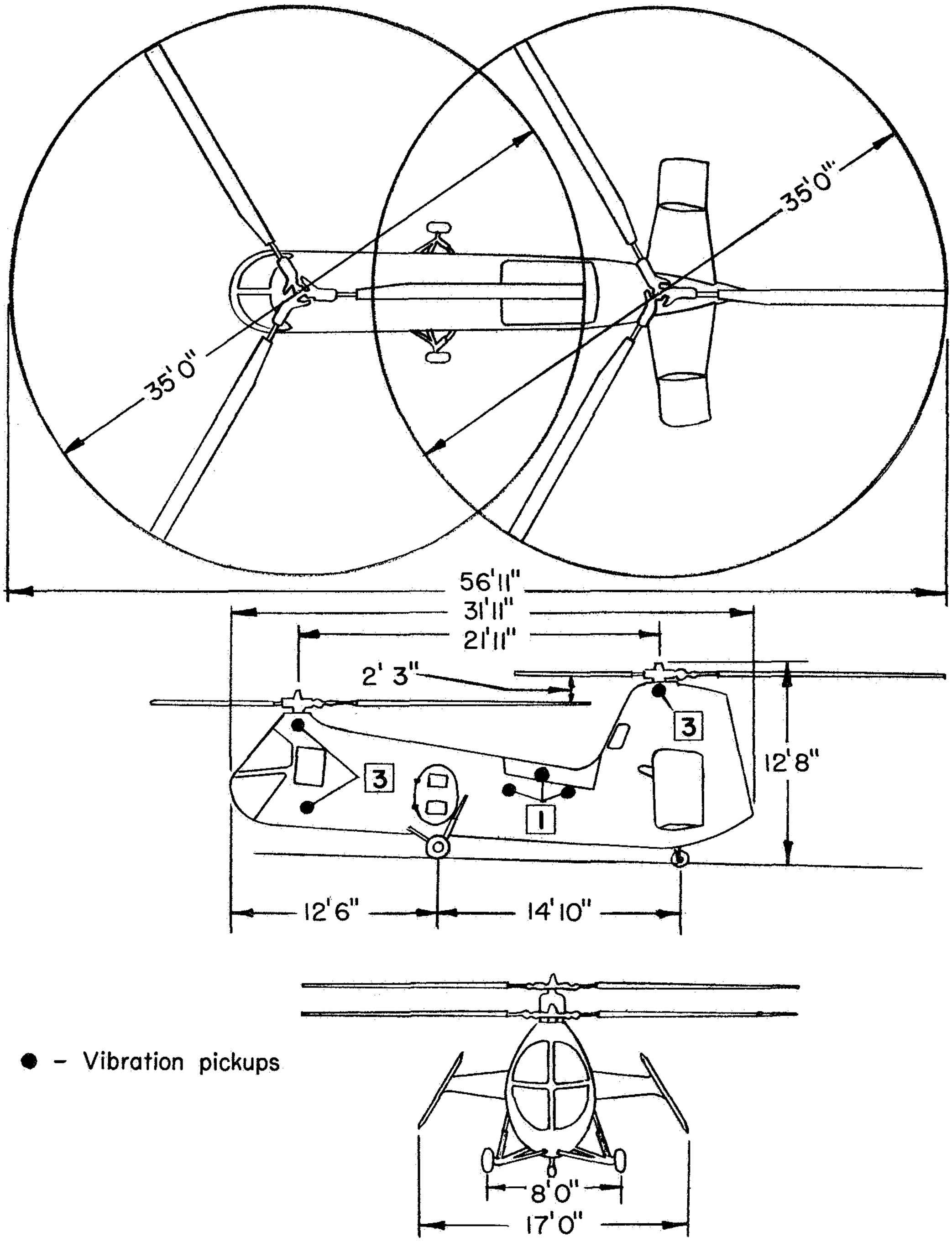


Figure 2.- Test helicopter showing location of vibration pickups and number of components measured.

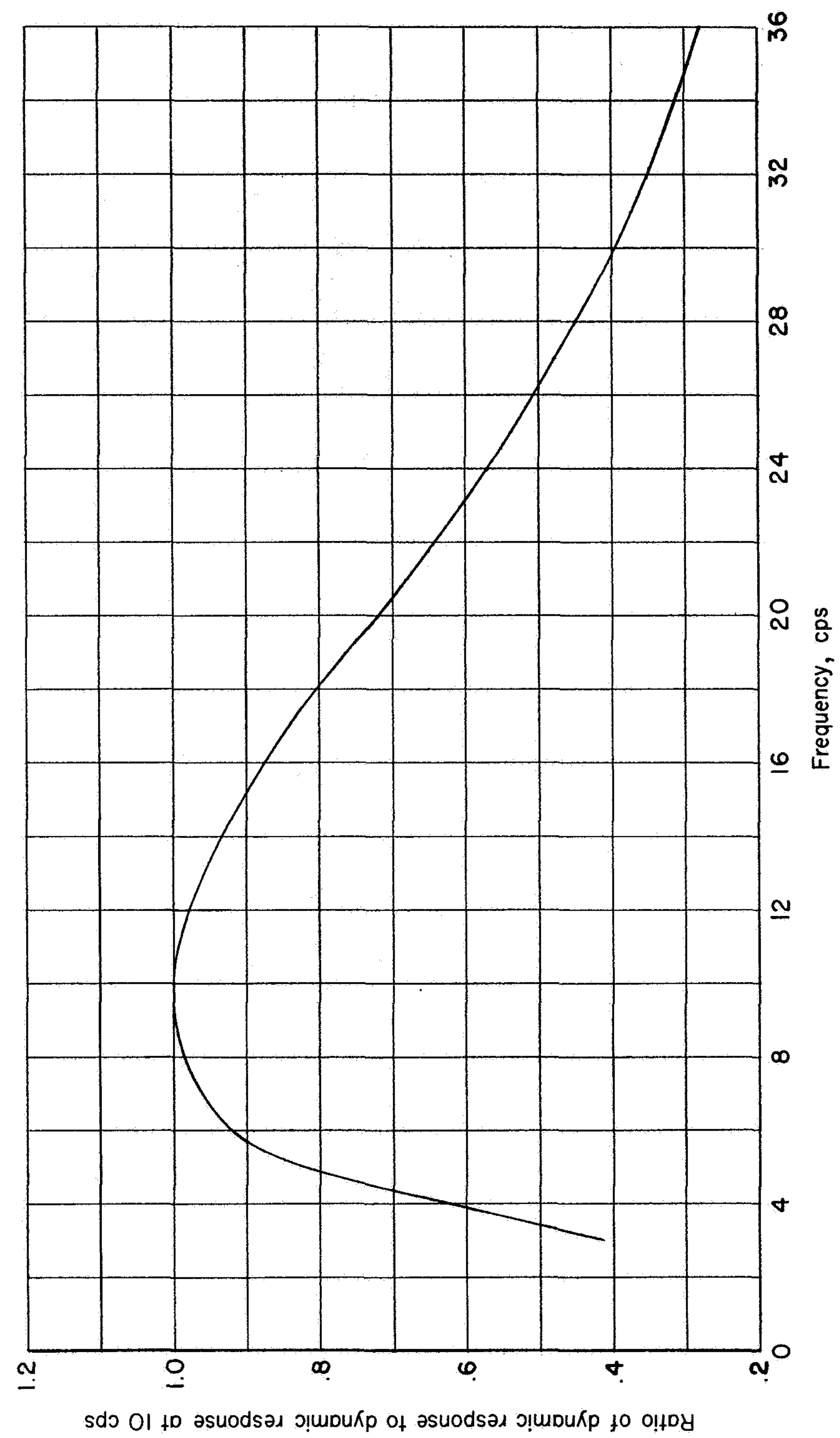
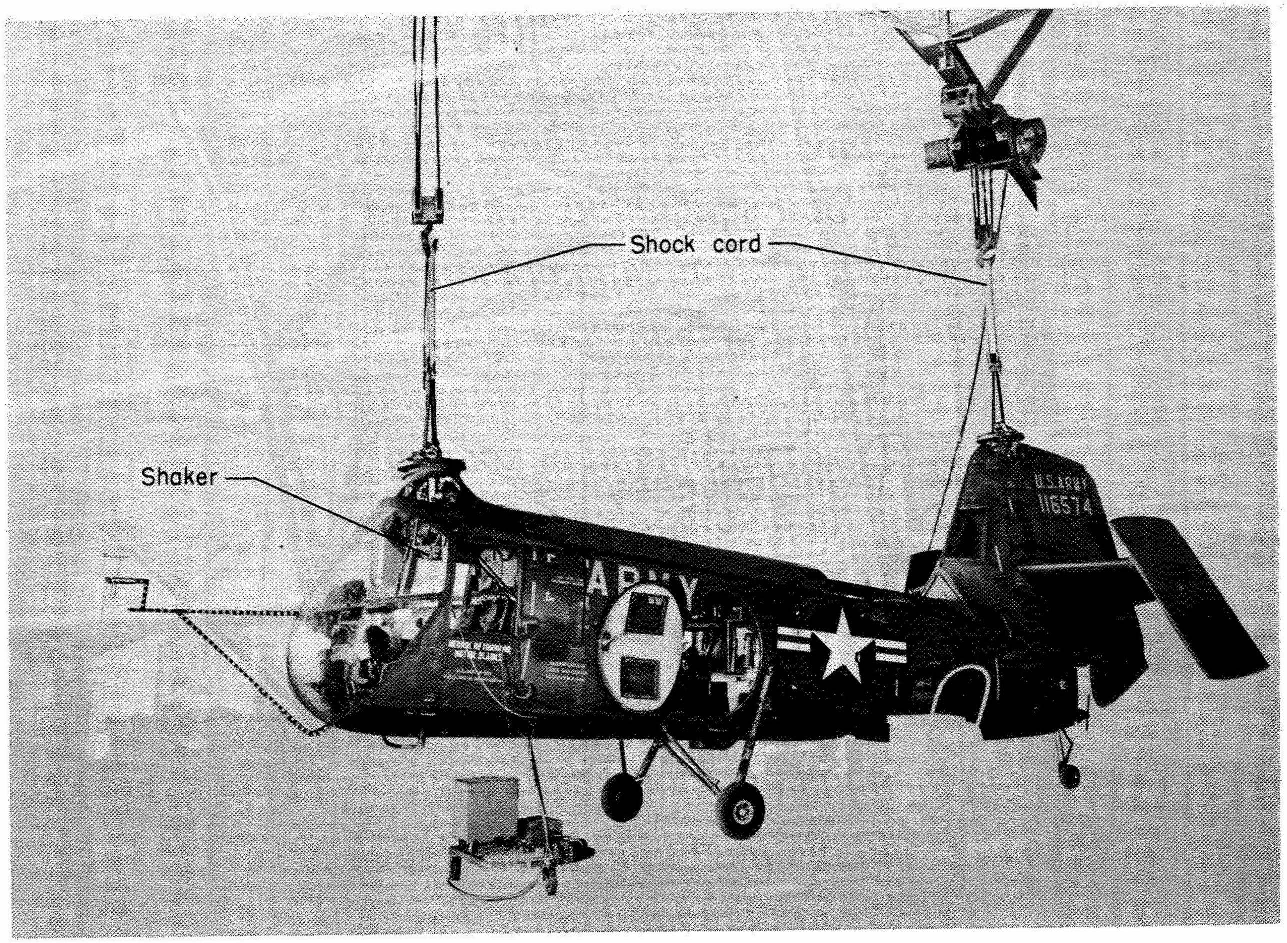


Figure 3.- Typical response curve for vibration-pickup—oscillograph combination used.



L-85686.1

Figure 4.- Test helicopter, with blade assemblies removed, showing method of suspension used for the ground vibration measurements.

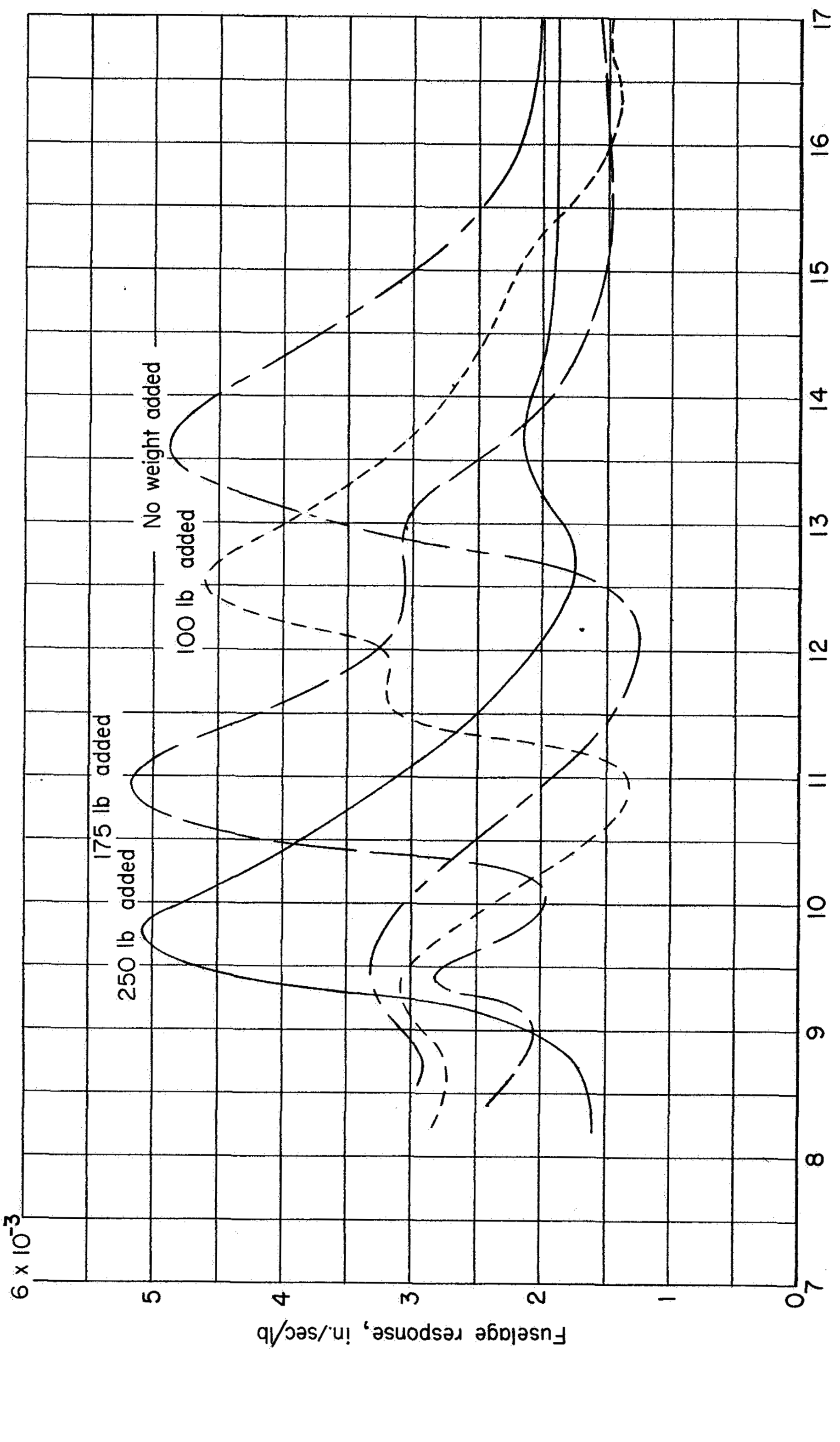


Figure 5.- Variation of fuselage response measured at the front rotor with sinusoidal excitation applied at the front rotor (both blade assemblies replaced by weights from the flapping pin outward).

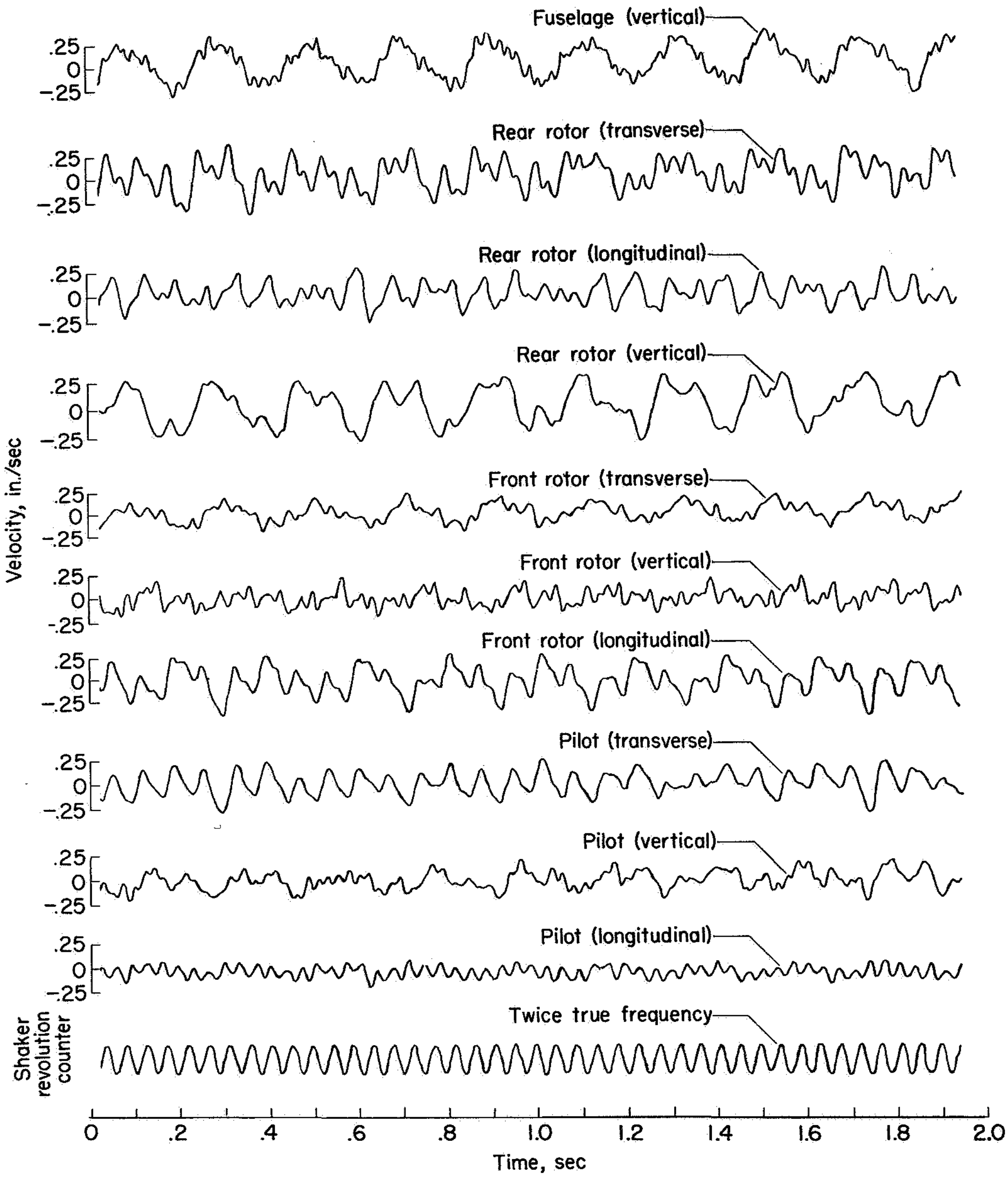
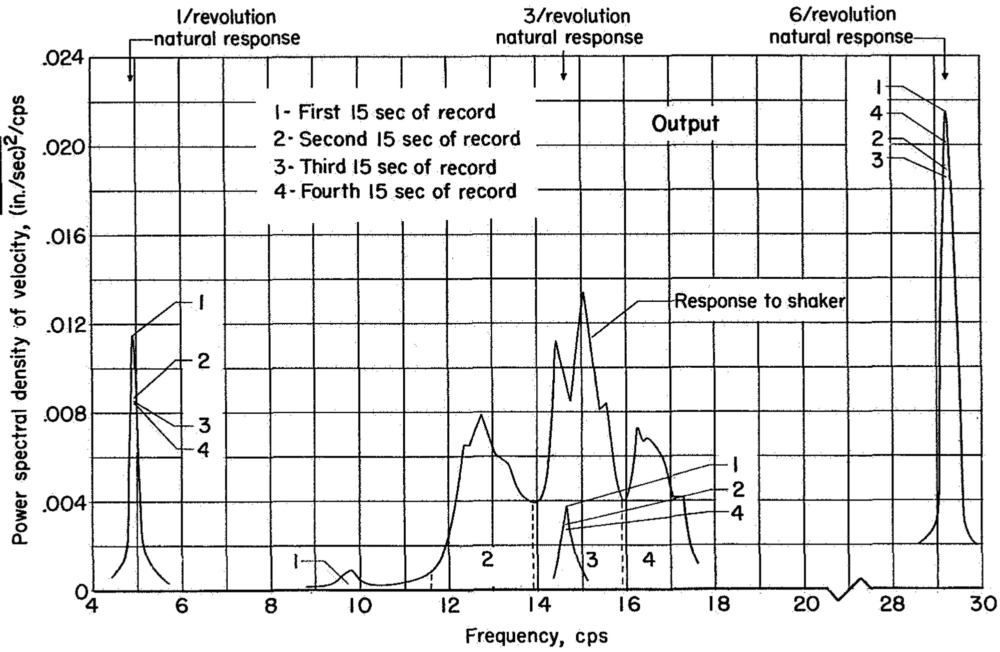
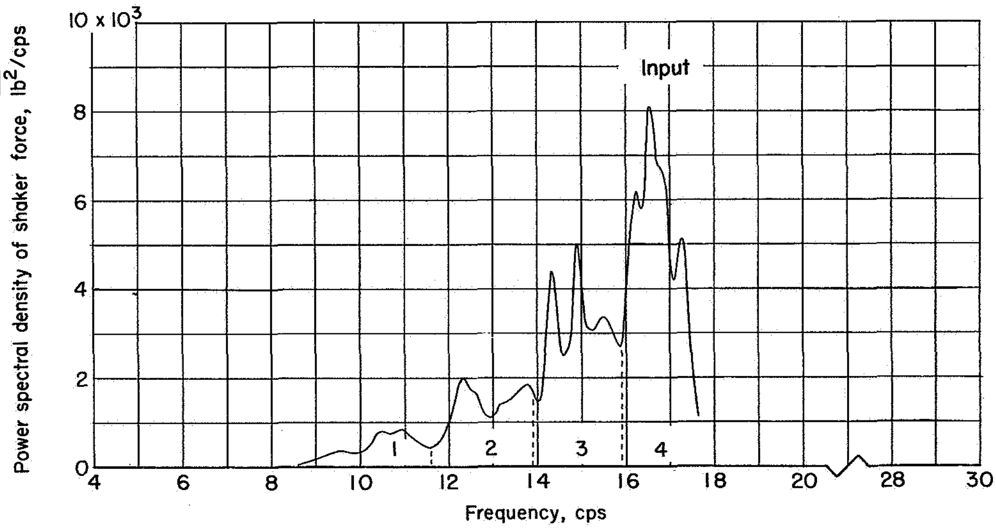


Figure 6.- Typical record of some of the velocity components measured. Forward speed, 55 knots; rotor speed, 290 rpm; shaker operating.

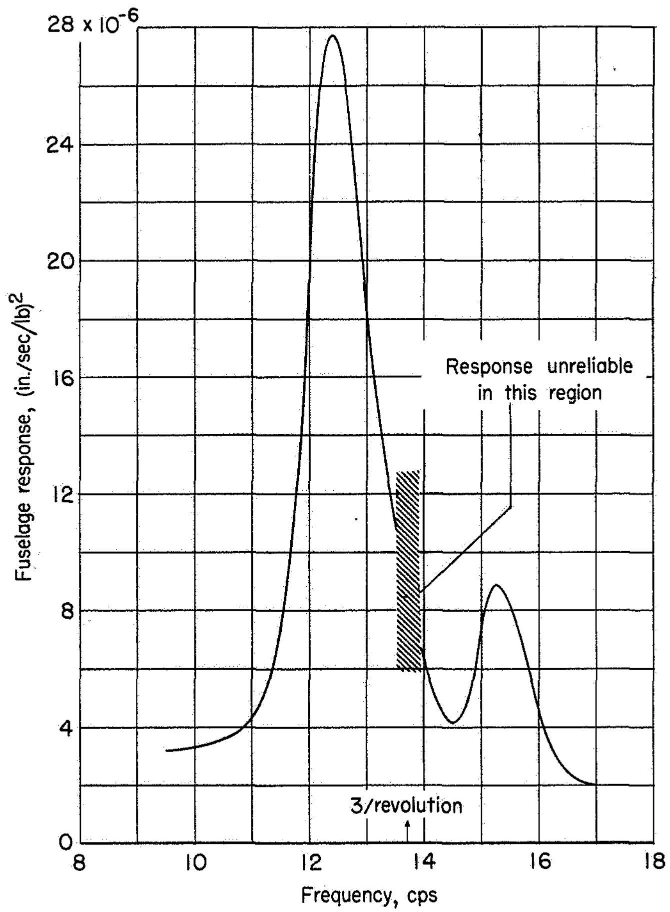


(a) Power spectrum of velocity at the front rotor.

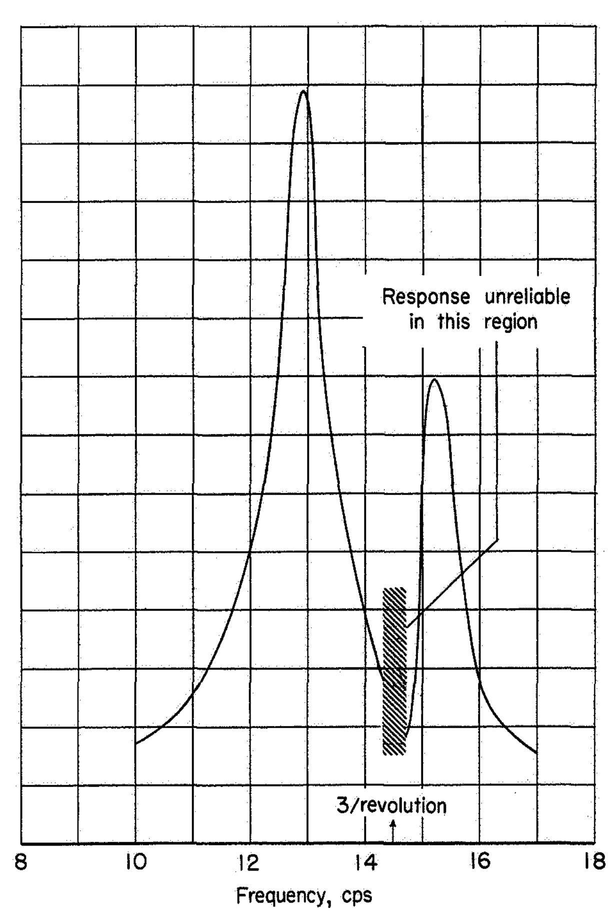


(b) Power spectrum of shaker force at the front rotor.

Figure 7.- Power spectra of the force and velocity at the front rotor with the shaker operating. Forward speed, 55 knots; rotor speed, 290 rpm; wood blade configuration.

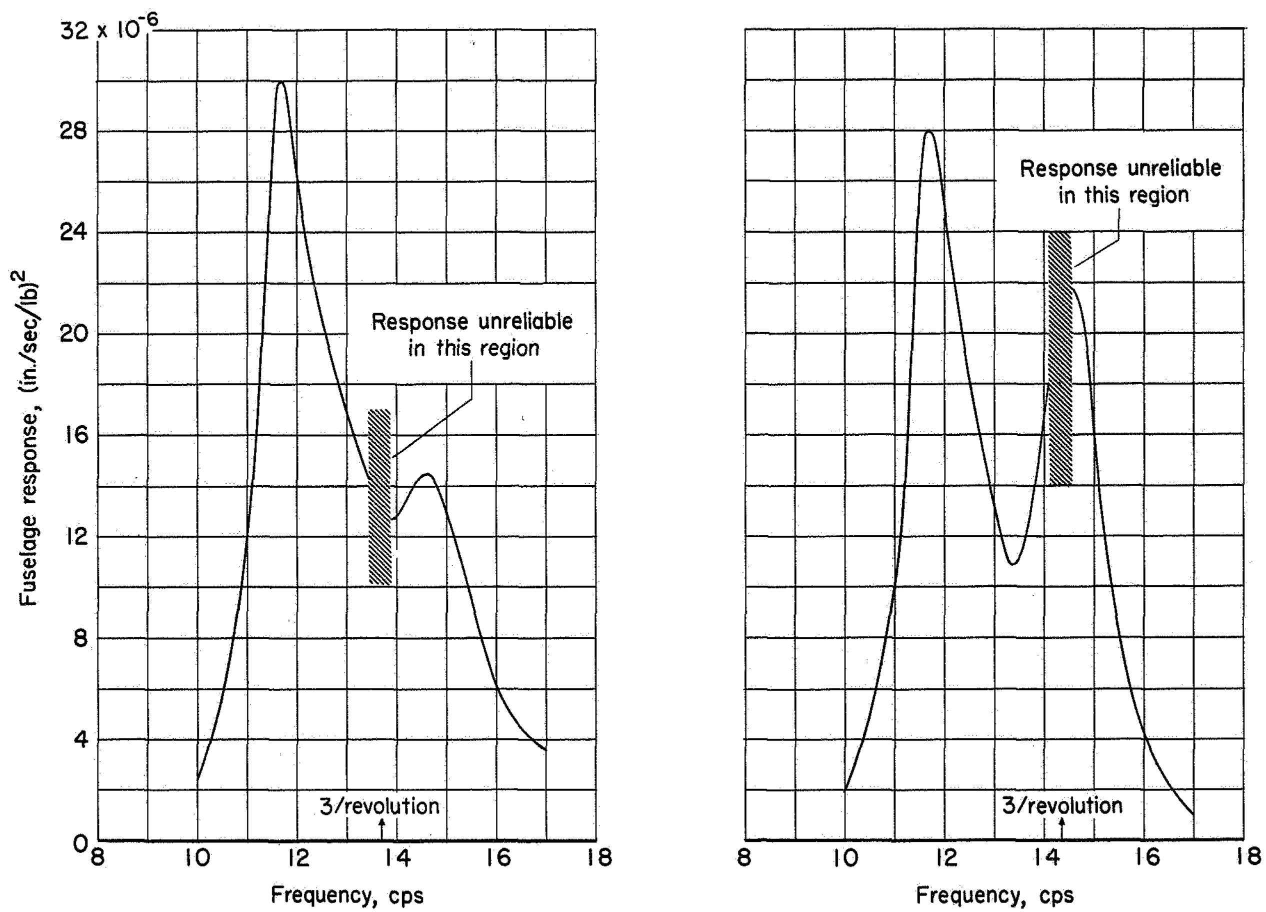


(a) 273 rpm.



(b) 290 rpm.

Figure 8.- Coupled response of helicopter structure, measured at the front rotor, showing the effect of change in rotor speed for the wood blade configuration at a forward speed of 55 knots.



(a) 273 rpm.

(b) 290 rpm.

Figure 9.- Coupled response of helicopter structure, measured at the front rotor, showing the effect of change in rotor speed for the metal blade configuration at a forward speed of 55 knots.

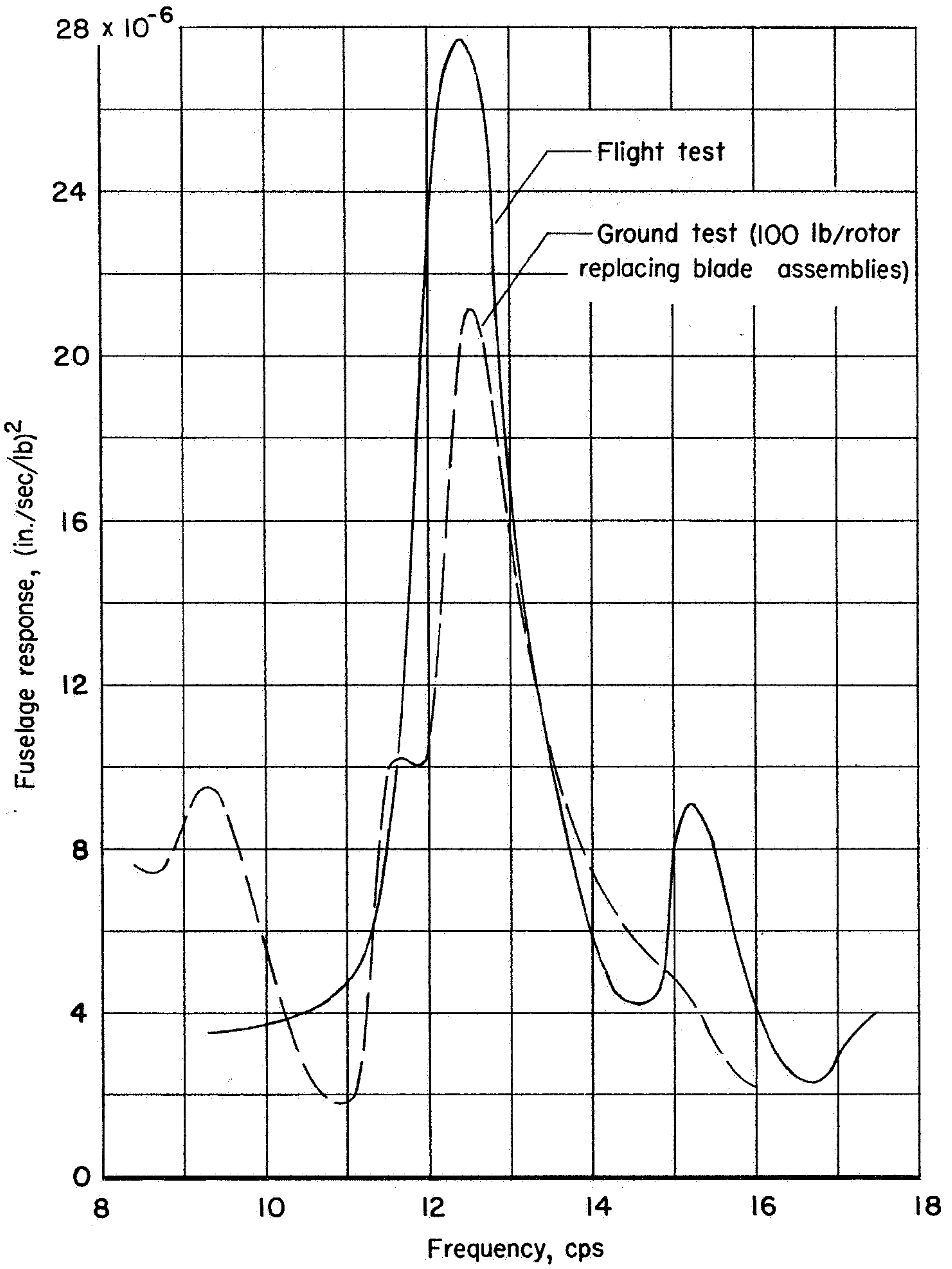


Figure 10.- Coupled response of helicopter structure measured at the front rotor for wood blade configuration (rotor speed, 273 rpm; forward speed, 55 knots) compared with ground-measured response (100 pounds at each rotor replacing blade assemblies from the flapping pin outward).

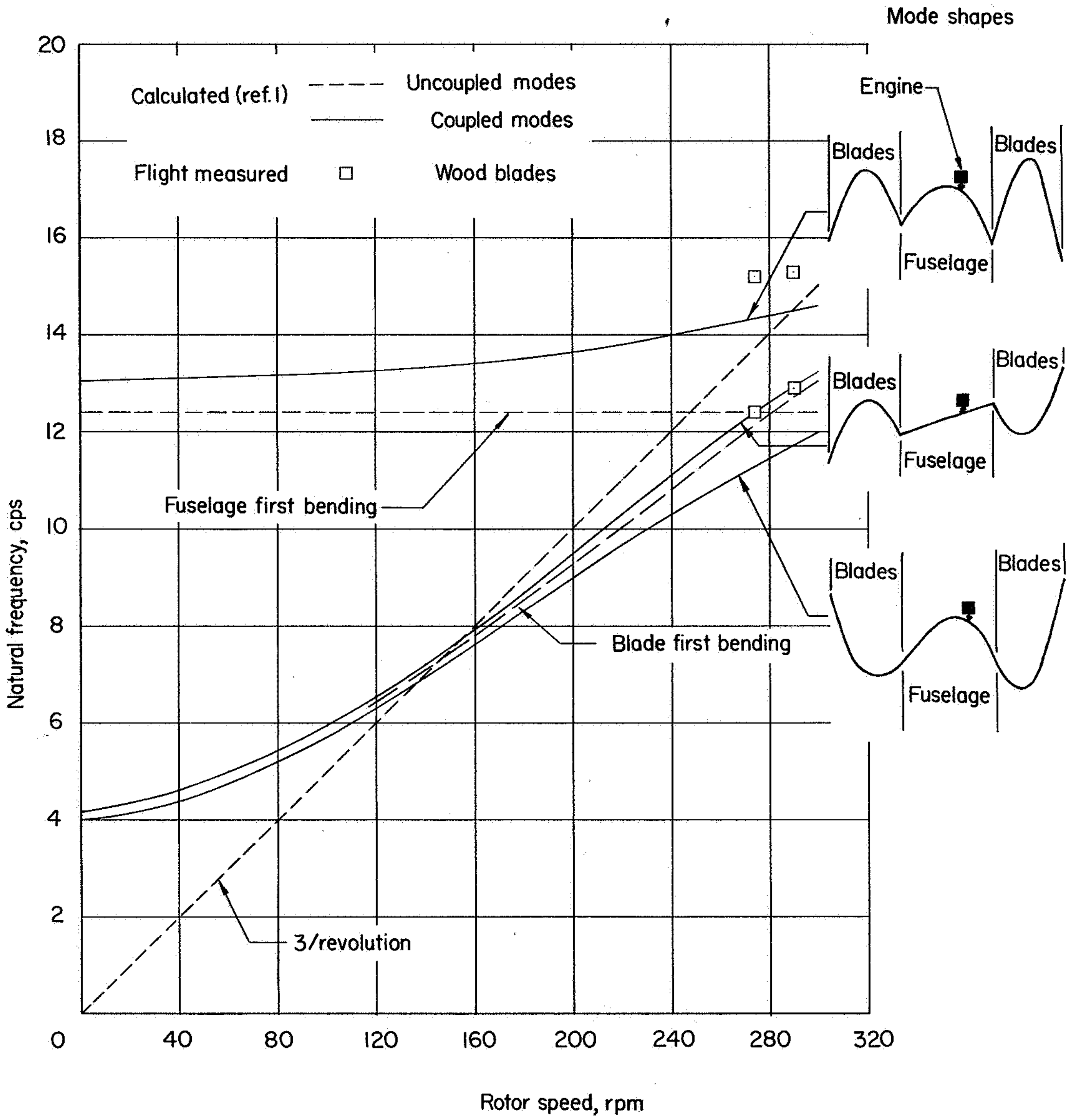


Figure 11.- A comparison of flight-measured peak response frequencies with those determined by theoretical methods.

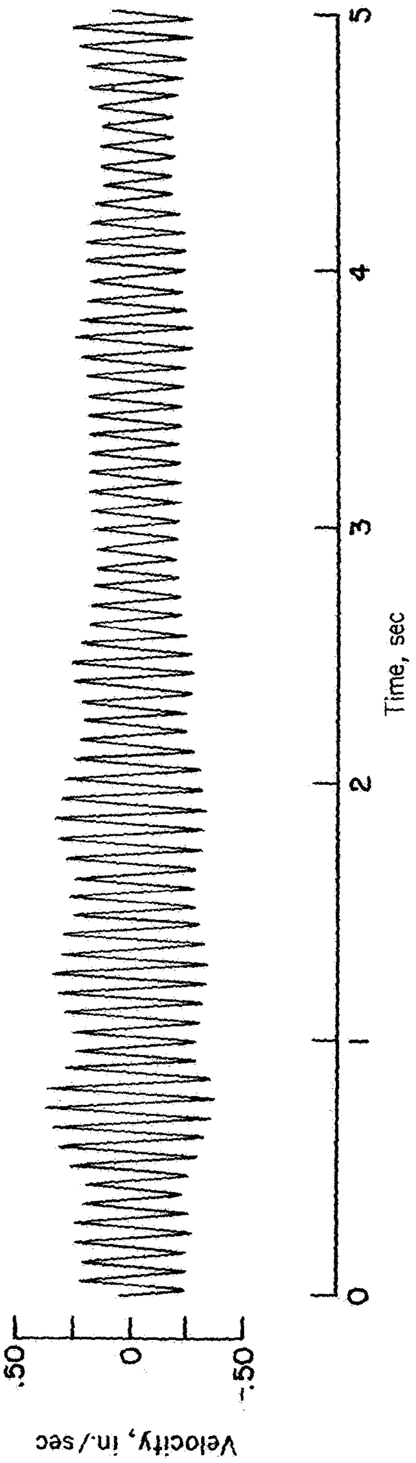
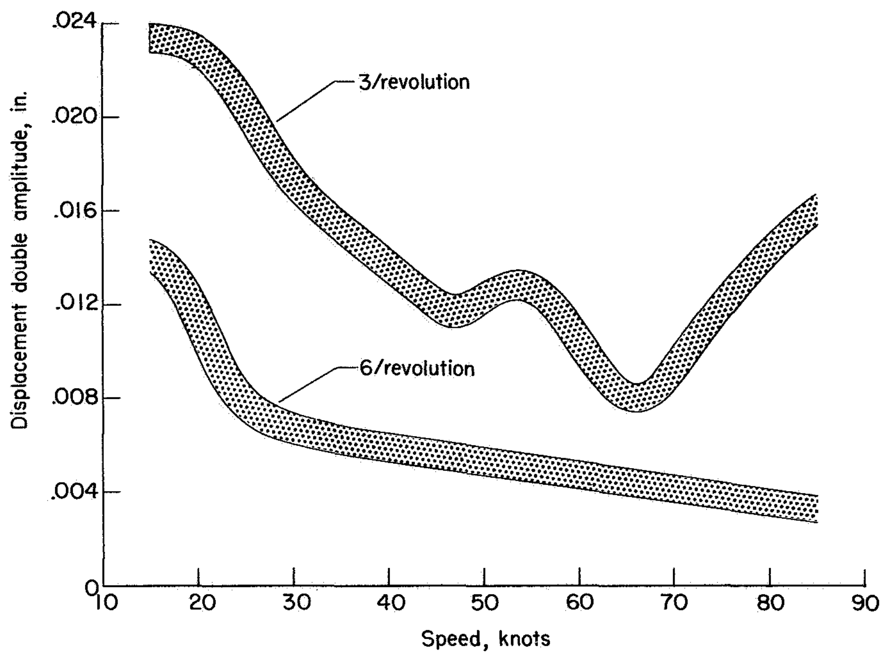
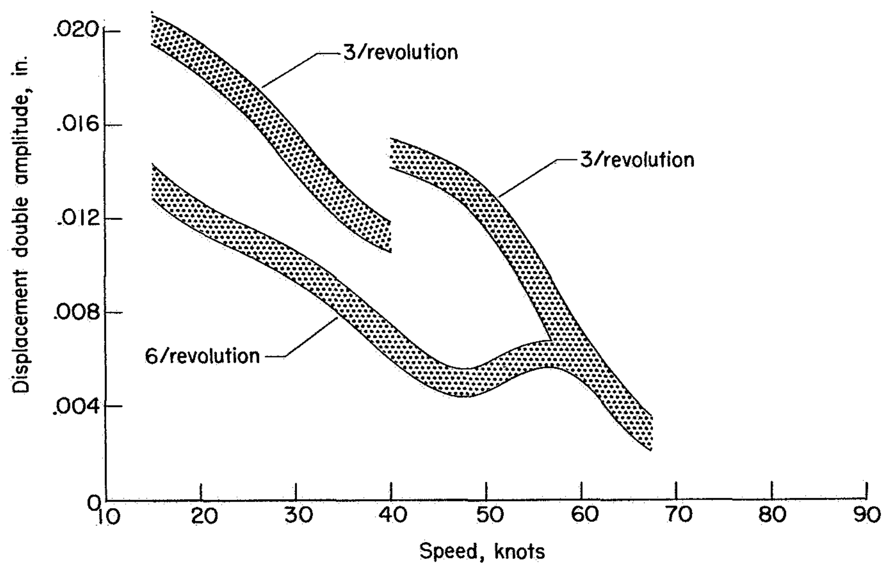


Figure 12.- Sample record, showing the time variation of the 3/revolution component.

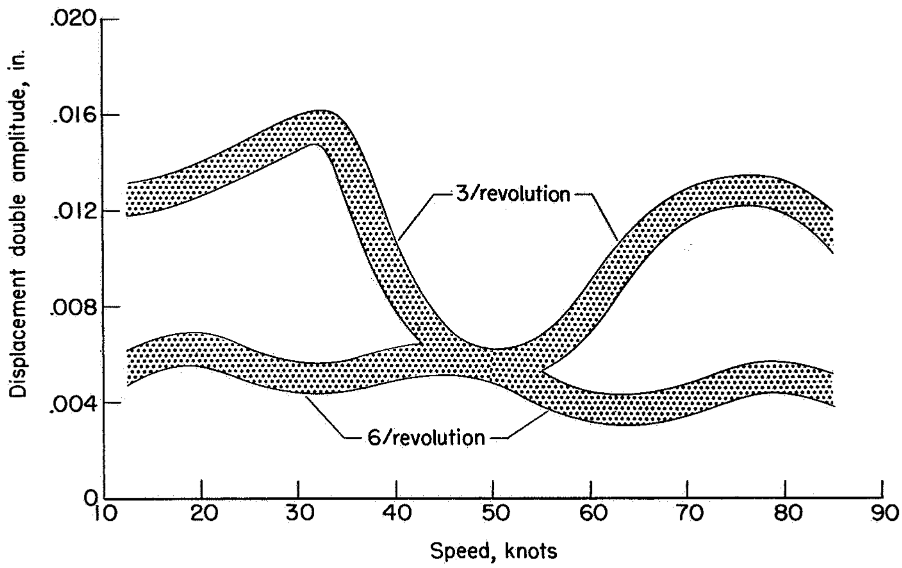


(a) Take-off power (37 in. Hg manifold press.).

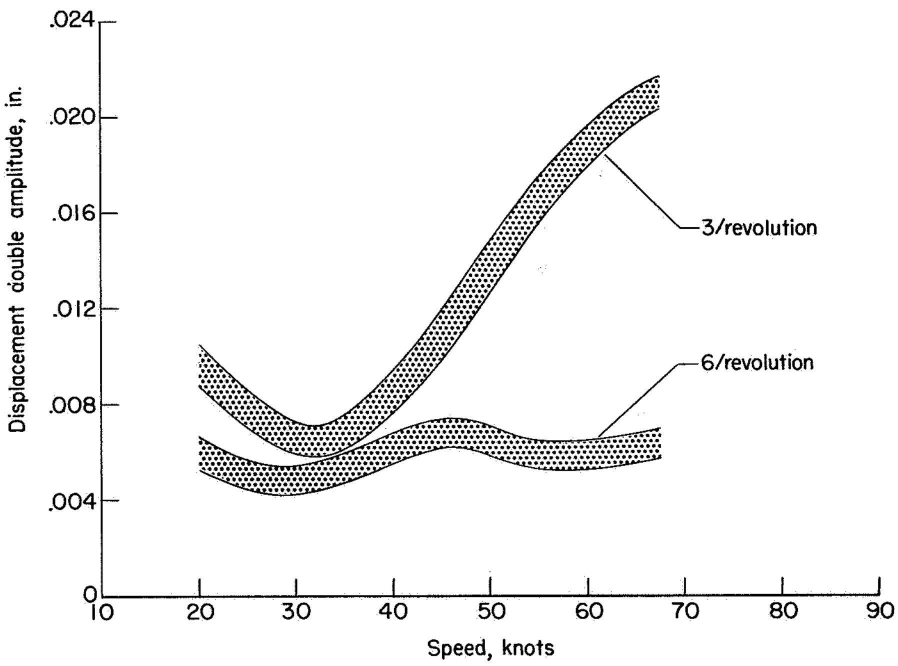


(b) Cruise power (30 in. Hg manifold press.).

Figure 13.- Variation of the principal harmonics of rotor speed with airspeed for four power conditions. Metal blade configuration.



(c) Low power (20 in. Hg manifold press.).



(d) Autorotation (15 in. Hg manifold press.).

Figure 13.- Concluded.